AlGaN/GaN MIS-HEMT Gate Structure Improvement Using Al_2O_3 Deposited by Plasma-Enhanced ALD

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Abstract - In this work we evaluate the influence of the Al_2O_3 ALD deposition technique on AlGaN/GaN MIS-HEMT structures. It has been found that using O_2 plasma as oxidizer instead of water could increase the threshold voltage considerably while greatly reducing gate leakage current. C(V) measurements have shown a very fast on/off transition even at 1kHz, with low frequency dispersion, while a record slope of 80mA/ decades was achieved between the on and off states through $I_d(V_g)$ measurements. Gate leakage currents were also drastically reduced with a measured average of $1e^{-11}$A/mm for a drain-source bias of 5V.

1. Introduction

AlGaN /GaN heterostructures are very promising for the elaboration of high-power and high frequency devices because of their excellent electrical properties such as a high breakdown voltage, a high electron saturation velocity and a high mobility of the 2D electron gas [1,2]. Furthermore, the possibility of growing high quality AlGaN/GaN heterostructures on large diameter Si substrates represent a good step forward in order to reduce the production costs.

The Metal Insulator Semiconductor (MIS) gate structure with the introduction of high dielectric constant (high-κ) materials as a gate dielectric represents one of the most promising ways to achieve viable power electronic devices [3,4]. Such structures can lead to effective gate leakage reduction compared to non-insulated Schottky gate structures. Among various insulators commonly used in the world of microelectronics, Al_2O_3 is mostly used for its deposition simplicity and offers advantages of a large band gap (9eV), a high dielectric constant (κ~10) and a high breakdown field. It has already brought very good results, though it often needs post deposition treatments and surface pre-conditioning [5]. Recently, plasma-enhanced atomic layer deposition (PEALD) has been given considerable interest since it can lead to MIS-gate structures with better performances compared to a Schottky-gate device [6].

2. Experimental

The AlGaN/GaN heterostructure was grown on silicon using a metal-organic chemical vapor deposition process. The epitaxy consists of a 2µm thick GaN buffer over which a 20nm $Al_{0.27}Ga_{0.73}N$ is then grown.

Device processing is carried through multiple lithography steps. Isolation is first made by MESA etching. Ti/Al Ohmic contacts are then formed at 900°C. A 10nm Al2O3 layer is then deposited at 250°C by ALD and the gate is deposited using a Cr/Au stack.

Regarding gate insulation, two different ALD techniques were compared. In both cases, tri-methyl aluminum (TMA) was used as a precursor, but in one case water is used as oxidizer while oxygen plasma is used in the other. We will respectively refer to these techniques as thermal and plasma-enhanced ALD. Both cases were also studied with or without in-situ nitrogen plasma-pretreatment (N_2PP). All the ALD processes and N_2PP were carried out on a Cambridge Nanotech Fiji.

This work is focused on capacitance/voltage C(V) and drain-current/gate-voltage $I_d(V_g)$ measurements analysis for the two different ALD techniques. The C(V) measurement were carried out on 400µm diameter diodes and Id(Vg) measurements were performed on 1mm width circular transistors with a 100µm gate length.

3. Results

As we can see in Fig.1, two distinct behaviors appeared depending on the oxidation process used during the ALD. The one using H_2O showed a stepped C(V) curve while the one using oxygen plasma led to a smooth and steep non-stepped on/off transition. The threshold voltage (V_{th}) was also increased from ~-9V to ~-5V. In the latter case, the same sharp behavior and steady capacitance below V_{th} was also obtained for all frequencies as low as 1kHz, while the H_2O samples led to negative capacitance below 50kHz. In both cases, N_2PP led to a higher C_{min} in the off-state.

Regarding $I_d(V_g)$ measurements, we see in Fig.2 the same increase in V_{th} as before, as well as a drastic gate leakage current (I_{leak}) reduction for the PEALD sample. Gate leakage current as low as $1e^{-12}$A/mm was measured, for an average of $1e^{-11}$A/mm for a drain/source bias V_{ds}=5V. The on/off ratio was increased from 10^3 to 10^9, with an I_{leak} reduction of more than 6 orders of magnitude. Speed of the transition between the on and off state was also greatly increased, and we were thus able to obtain a record sub-threshold slope of 80mA/decades. Again, N_2PP led in both cases in a higher I_{leak} and a lesser depletion of the canal.

Another interesting property of using PEALD is its capacity to enhance device performances without any surface pre-treatment. If we look at Fig.3, we can clearly see that without any preparation of the AlgaN surface, we obtain a relatively poor Schottky device. But if we apply a 6nm PEALD Al_2O_3 before the gate deposition, we can clearly see that the device is now switching more rapidly between the on and off state, for a threshold voltage relatively similar.

4. Interpretation

Regarding C(V) and $I_d(V_g)$ results, the V_{th} improvement can be linked to a reduction of trapped charges through the O_2-plasma ALD deposition technique compared to thermal ALD. Furthermore, the better quality of the O_2-plasma oxide is confirmed by stable low frequency measurements, while the negative capacitance obtained with H_2O deposition is characteristic of a leaky behavior. Overall reduction of traps can also be confirmed by the sharper transitions between the on and off states.

Those traps can be associated to the carbon contamination of the AlGaN surface. Thus the improvement of the results between the two deposition techniques may come from a better carbon removal at the surface during the first cycles of plasma assisted ALD. If we look at Fig.4, 5 and 6, we can see that the surface after only three ALD cycles looks similar to a surface to which an oxygen plasma only was applied. In both cases, the traditional terrace-like aspect of the surface was restored, and previous XPS studies confirmed such a treatment could greatly reduce carbon contamination [7].

In case of thermal ALD, we also observed through TEM images non-uniformity of the Al_2O_3 deposition, with a detachment of the oxide layer at the gate periphery. This could explain the stepped behavior of the device and can thus be assimilated as having two capacitances in parallel [8].

Regarding the N_2PP hindering the canal depletion, AFM studies on Fig. 6 and 7 show that applying such a pretreatment to our samples increases the R_{ms} roughness compared to Fig.5 and 4 respectively. This roughness increase may be related to the higher leakage current and degraded off-state capacitance.

5. Conclusion

In this study, we have shown that using O_2-plasma instead of water during the oxidation steps of the Al_2O_3 ALD deposition drastically improves our device performances. An average increase of 4V in the threshold voltage was obtained while the gate leakage current was reduced by 7 orders of magnitude. The on/off ratio was also greatly increased to 10^9 with a record on/off slope of 80mV/dec. Furthermore, these good results were achieved without specific surface preparation or post-deposition treatments, thus proving that the MIS-HEMT structure is a viable one for future power applications.

6. Perspectives

Complementary XPS and AFM studies will be conducted in order to precise the AlGaN surface mechanisms involved during ALD first steps. Thick thermal and PEALD Al_2O_3 layers will also be analyzed to better understand the differences induced by the two deposition techniques in terms of high-κ quality.

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References

[1] O. Ambacher et al, Journal of Applied Physics, 87 (2000) 334-344
[2] R. Oberhuber et al, Applied Physics Letters, 73 (1998) 818-820
[3] N. Maeda et al, Microelec. Proceedings of SPIE, vol. 7216 (2009)
[4] T. Hashizume et al, Japanese Journal of Applied Physics, The Japan Society of Applied Physics, 43 (2004) L777-L779
[5] O. Saadat and T. Palacios, Solid-State Device Research Conference, (2011) 287-290
[6] R. Lossy et al, Journal of Vacuum Science and Technology A, 31 (2013)
[7] R. Meunier et al, ECS Meeting Abstracts, MA2012-02 (2012) 2571
[8] R. Escoffier et al, SOI Conference (SOI), 2012 IEEE International (2012)

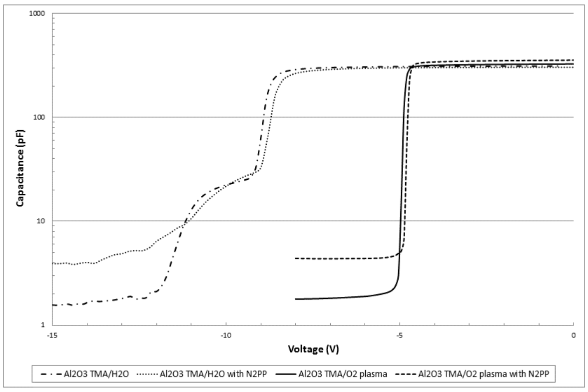

Fig.1: C(V) measurements for MIS diodes with 10nm Al_2O_3, with and without N_2PP.

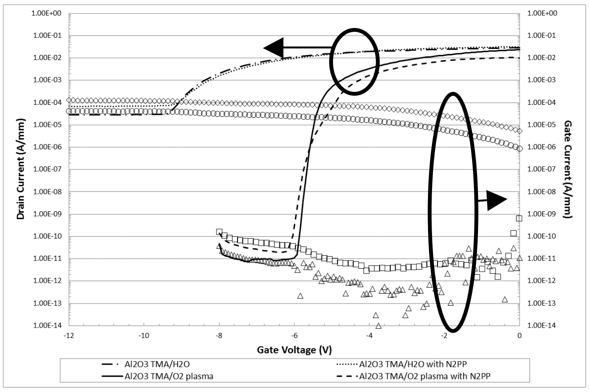

Fig.2: $I_d(V_g)$ measurements for MIS diodes with 10nm AL2O3, with and without N_2PP for V_{ds}=5V.

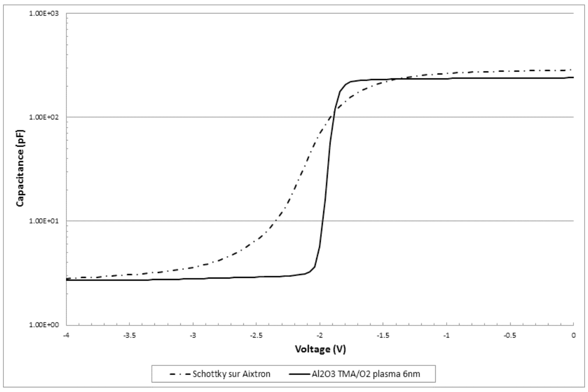

Fig.3: C(V) characteristics for Schottky and 6nm PEALD deposited Al_2O_3 MIS diodes .

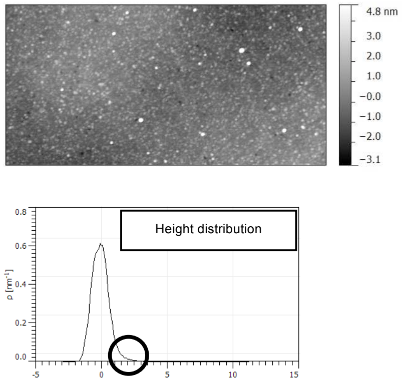

Fig.4: AFM picture and height distribution of reference sample. Grainy aspect and small asymmetry in height distribution. R_{ms}=0.72nm

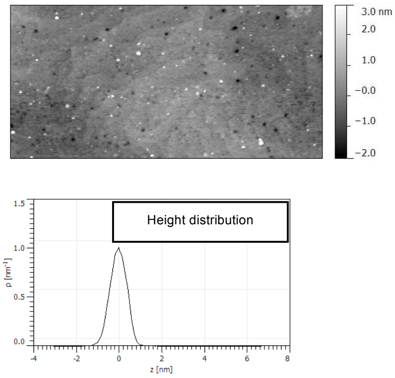

Fig.5: AFM picture and height distribution of a reference sample treated with a 2min oxygen plasma. Recovery of the terrace like aspect and reduction of roughness. Rms=0.43nm

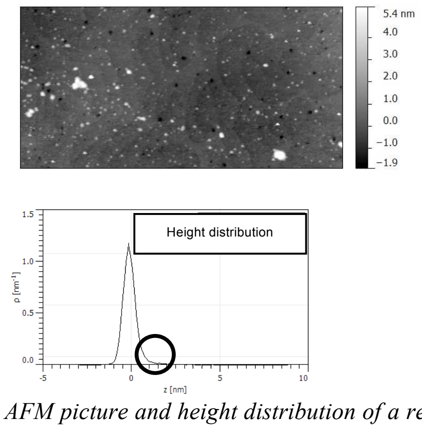

Fig.6: AFM picture and height distribution of a reference sample after 3 cycles of ALD using O2- plasma steps. Terrace like aspect is visible with a reduced roughness. Rms=0.63nm. Small asymmetry in height distribution is related to N2 plasma pre-treatment.

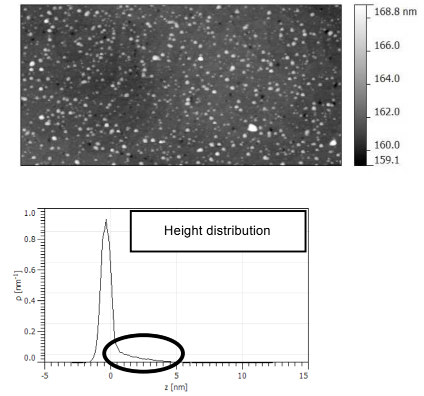

Fig.7: AFM picture and height distribution of a reference sample treated only with N_2 plasma pre-treatment. Roughness increase and strong height distribution asymmetry. Rms=1.02nm